GEOCHEMICAL ZONING IN THE MOON; S. R. Taylor, Australian National University, Canberra, and The Lunar Science Institute, Houston, Texas; and P. Jakeš, Geological Survey of Czechoslovakia, Praha, and The Lunar Science Institute, Houston, Texas, 77058.

The lunar samples returned by the Apollo missions display many unique geochemical features, compared to terrestrial rocks or meteorites. These include (1) depletion of volatile elements (Rb, K, Tl) (2) depletion of siderophile elements, with volatile elements (e.g. Ag) depleted more than refractory ones (e.g. Ir) (3) enrichment of many refractory elements (Ba, Zr, Hf, REE, Th, U) by two orders of magnitude over primitive CCI abundances (4) high abundances of Mg + Cr in aluminous crustal rocks (5) similarity of volatile/involatile element ratios (e.g. Cs/U, K/Zr, K/La) in mare and highland rocks (6) high Cr/Ni ratios (7) Eu anomalies (8) occurrence of several types of mare basalts with varying Mg/Fe, Ti, REE and Eu depletion.

We attempt here to reconcile the geochemical information with the geophysical constraints and the sequence of geological events. We assume that the Moon accreted from refractory material from which the volatile elements (Rb, Pb, Tl, Bi, Cs etc.) had already been depleted.[1,2] The volatile siderophile elements (Ag) were depleted, more than the refractory ones (Ir) as shown by Re/Ir/Ni/Au/Ag ratios.[3]

The accretion was homogeneous since there is (a) a good correlation between volatile/involatile element ratios (e.g. Cs/U, K/Zr)[3,4] in both highland and mare samples, (b) the element distribution in crustal rocks is governed not by volatility differences, but by ionic radius and valency, indicating crystal-liquid equilibria.[5,6] If heterogeneous accretion models are excluded, very efficient large scale element fractionation must occur, implying melting of most of the Moon. The heat source is accretionary. Initial cooling takes place by convection.[7] The lunar interior is highly reduced because of lack of volatiles. Large scale melting is consistent with the lack of major seismic discontinuities between 60 and 1000 km.

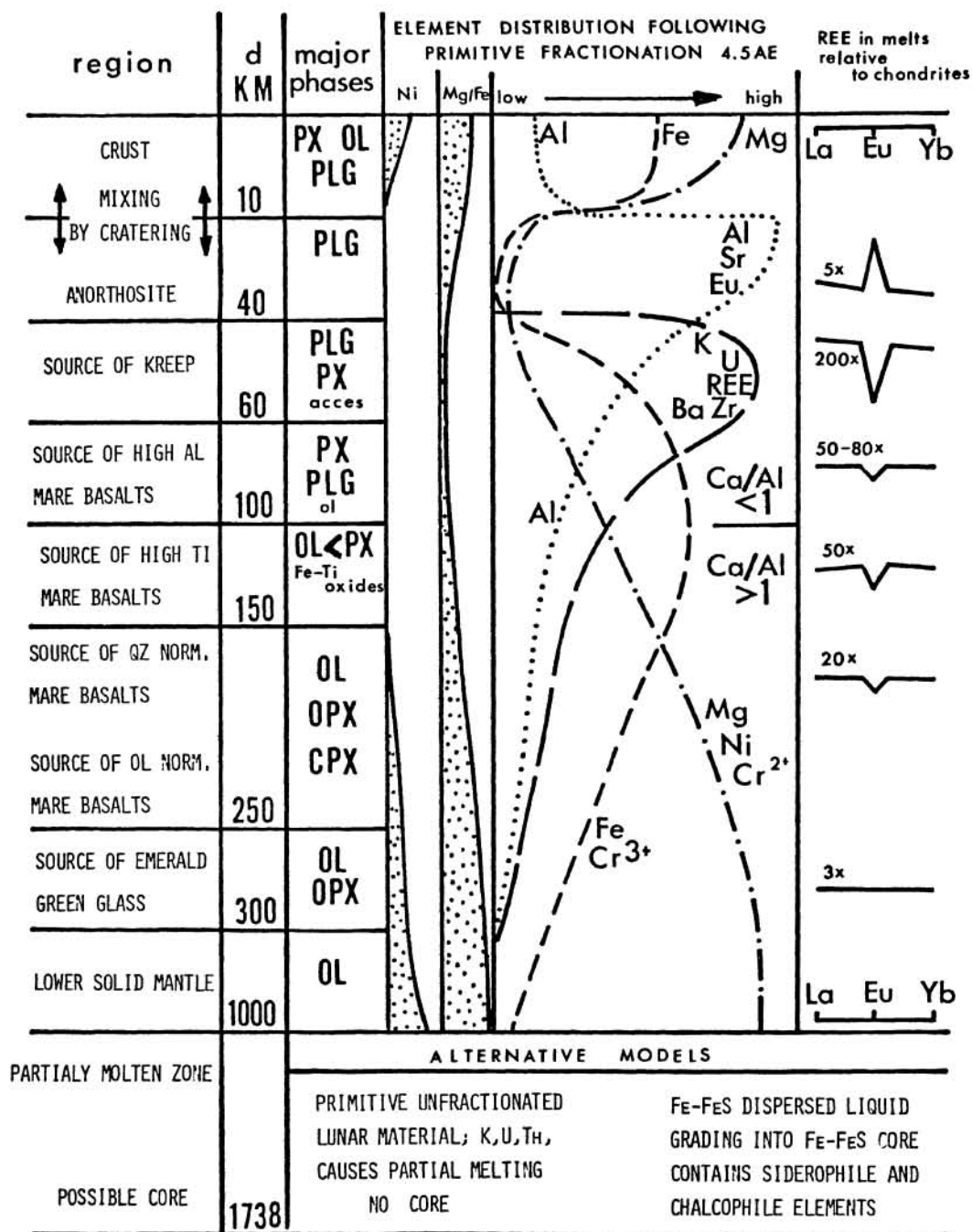Two alternative models may account for the deep lunar interior (below 1000 km):
(a) An immiscible Fe-FeS liquid sinks to form a core effectively removing most siderophile and chalcophile elements. The core radius is restricted to < 700 km by the moment of inertia (0.395). Enough sulfur is retained to form FeS.[8] The partially liquid zone below 1000 km is interpreted as due to dispersed FeS in olivine-orthopyroxene matrix. The magnetic field results from a core dynamo.
(b) The melting did not extend below 1000 km. The center is primitive unfractionated material, now partially molten due to trapped K, U and Th. This model precludes core formation, since sinking Fe-FeS will drive incompatible elements upwards. This model is a better fit for the P wave velocities. The magnetic field is external.[9]
The choice between these depends critically on the amount of the early siderophile and chalcophile element depletion. If the siderophile elements were accreted, a lunar core is required to remove them.

Following accretional melting, the first silicate phase to separate is Mg-rich olivine, which removes Ni^{2+}, and lesser amounts of Cr^{2+} and Co^{2+}. As crystallization proceeds, orthopyroxene precipitates. In the low pressure (< 50 kbar) environment, most cations except Mg, Fe, Ni, Co and Cr^{2+} are excluded from the olivine and orthopyroxene lattice sites, and migrate upwards. These include Ca and Al. The high Cr^{3+} values indicate that separation of clinopyroxene below 300 km was minor. A frozen crust quickly developed, although continually broken up by the declining meteoritic bombardment. This frozen surface layer, analogous to a chilled margin retained high concentrations of Mg, Cr etc. in near surface regions. These elements are not derived from chondritic meteorites, which would have contributed high Ni, Ir etc. Because of the refractory nature of the total lunar composition, and the low abundance of volatiles and K, a granitic type residual phase does not form at first, and a Ca-Al rich residuum develops. Increasing crystallization at depth leads to an increasing concentration of these elements, trapped under the frozen surface layer. When the concentration of Al reaches 12-17% Al_2O_3, An-rich plagioclase precipitates, and concentrates beneath the frozen surface whereas the Mg-Fe phases sink. The Ca-Al rich region incorporates Sr^{2+} and Eu^{2+}, but most other elements are unable to enter the Ca^{2+} sites.

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region	d KM	major phases	ELEMENT DISTRIBUTION FOLLOWING PRIMITIVE FRACTIONATION 4.5 AE				REE in melts relative to chondrites
			Ni	Mg/Fe	low ⟶	high	La Eu Yb
CRUST	10	PX OL PLG			Al	Fe Mg	
⇕ MIXING ⇕ BY CRATERING		PLG				Al Sr Eu	5x
ANORTHOSITE	40						
SOURCE OF KREEP	60	PLG PX acces				K U REE Ba Zr	200x
SOURCE OF HIGH AL MARE BASALTS	100	PX PLG ol			Al	Ca/Al <1	50-80x
SOURCE OF HIGH TI MARE BASALTS	150	OL<PX Fe-Ti oxides				Ca/Al >1	50x
SOURCE OF QZ NORM. MARE BASALTS		OL OPX CPX					20x
SOURCE OF OL NORM. MARE BASALTS	250					Mg Ni Cr²⁺	
SOURCE OF EMERALD GREEN GLASS	300	OL OPX			Fe Cr³⁺		3x
LOWER SOLID MANTLE	1000	OL					La Eu Yb
PARTIALY MOLTEN ZONE			ALTERNATIVE MODELS				
POSSIBLE CORE	1738		PRIMITIVE UNFRACTIONATED LUNAR MATERIAL; K,U,TH, CAUSES PARTIAL MELTING NO CORE		FE-FES DISPERSED LIQUID GRADING INTO FE-FES CORE CONTAINS SIDEROPHILE AND CHALCOPHILE ELEMENTS		

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As crystallization proceeds in both top (crustal Ca-Al) and bottom (mantle Fe-Mg) regions, additional fractionation changes the Mg/Fe ratio, produces zones of Fe-Ti oxide accumulation and further removes the siderophile elements. Those elements unable to enter the plagioclase above or the Mg-Fe sites below are trapped between. In this zone, all the remaining elements concentrate. These include K, Ba, Rb, Cs, REE, Th, U, Zr, Nb. Thus following the primordial fractionation, a chemically zoned Moon is produced.

A schematic version of this is shown in Figure 1. The crustal zonation established at about 4.5 aeons is changed very quickly. The declining stages of the meteoritic bombardment pulverize the chilled zone and larger impacts mix in the underlying anorthosite. The high concentration of heat-producing elements K, U and Th (and Zr, Hf, REE etc.) beneath the plagioclase zone provide the high element abundances for the Fra Mauro or KREEP basalts. Possibly this zone did not solidify[10] but the residual liquids invaded the crust, where impact mixing of the primitive surface, layer, the plagioclase and the residual liquids produced the parent material for the anorthositic gabbro (highland basalt) and the Fra Mauro basalts.[11] This stage continues to 3.9 aeons, culminating in the production of the ringed basins and the cessation of the intense highland cratering. The high heat flow (0.7 HFu) is due to the near surface concentration of most of the lunar K, U and Th.

Partial melting next occurs in successively deeper layers as the lesser amounts of the heat producing elements induce partial melting, and a succession of 'mare-type' basalts are erupted. The first of these are the aluminous (12-13% Al_2O_3 basalts (e.g. 14053, 14072) from shallow depths beneath the KREEP source layer.[12] These overlap with the later stages of the bombardment, and predate the Imbrium collision in part, as shown by their presence in Fra Mauro breccias. Next (3.8-3.6 aeons), the Ti-rich Apollo 11 and 17 basalts are erupted from a zone where Fe-Ti oxides accumulated. They have ~ 1 ppm Ni. Later (3.4-3.2 aeons) the Apollo 12 and 15 quartz and olivine normative basalts were extruded. These contain nickel indicating extensive partial melting involving olivine, and show evidence of near surface fractionation. The deepest material[13] erupted is the Apollo 15 emerald green glass (15426) with 180 ppm Ni and primitive REE patterns, low total REE (3-5X chondrites) and no Eu anomaly.

The model is consistent with a total Moon composition, relative to primitive Solar System abundances, highly depleted in volatile and strongly siderophile elements and enriched 2-5X chondrites in the refractory elements.

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